RADIATION SAFETY STUDY GUIDE
FOR USERS OF RADIATION GENERATING DEVICES

Environment, Safety, Health and Assurance
Ames Laboratory-USDOE

APPROVAL RECORD

- Reviewed by: Document Control Coordinator (Hiliary Burns)
- Approved by: ESH&A, Health Physicist (Mike McGuigan)
- Approved by: Manager, Environment, Safety, Health & Assurance (Sean Whalen)

TABLE OF CONTENTS

Contact Person	Michael McGuigan	**Revision**	6
Document	Guide 10202.001	**Effective Date**	04/01/17
		Review Date	04/01/20

AMES LABORATORY
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

1.0   INTRODUCTION

Radiation generating devices are important tools in various areas of modern research. However, the x-rays produced by such equipment can pose a hazard to human health. For this reason, special precautions must be observed when these devices are used.

Ames Laboratory, in conjunction with the Department of Energy, is firmly committed to having a radiological control program of the highest quality. This program as outlined in the Ames Laboratory Radiological Protection Program (RPP), as mandated by Title 10, Federal Code of Regulations, Part 835 (10 CFR 835), requires that managers and supervisors at all levels be involved in the planning, scheduling and conduct of radiological work. This directive also requires that adequate radiological safety shall not be compromised to achieve production or research objectives.

At Ames Laboratory each new project which involves the use of a radiation generating device must be approved by the Division/Institute/Program Director via Readiness Review. This approval includes specific authorization by Environment, Safety, Health & Assurance (ESH&A) and by the ALARA (As Low As Reasonably Achievable) Committee. Minor changes to previously approved projects, such as the addition of new personnel, require the approval of ESH&A. No student or member of the staff or faculty at Ames Laboratory may use X-ray equipment without this written approval. Additional details concerning application for initial authorization of a project are contained in the [Ames Laboratory Radiation Protection Program Plan](#). Requirements for the authorization of an individual to work on a previously approved project are described in the following subsections.

This study guide should be used as a companion to the Laboratory's Radiation Protection Program Plan (RPP). The RPP describes the radiation protection program to the radiation workers at Ames Laboratory. All individuals who wish to use x-ray equipment at Ames Laboratory must review this guide and complete the associated examination before they can be authorized to use the equipment. Additional authorization requirements are also addressed in this guide. Questions concerning this guide or the authorization process should be directed to ESH&A at 294-2153.

1.1   Training Requirement

Each individual who wishes to be authorized to use radiation generating devices (RGD) at Ames Laboratory must first receive training concerning the radiation hazards associated with the use of the equipment, the function and importance of the equipment's safety devices, proper operating procedures, and procedures to follow in the event of a suspected radiation exposure. The training is provided, in part, through this guide, written examination and radiation survey instrument training. Instructions concerning dosimetry rings, usage, handling and exchange periods are also part of the training process. Dosimetry is issued by ESH&A, Health Physics group.

1.2   On the Job Training

This written guide does not replace the requirement that the Group Leader or an appropriate alternate provide practical, hands-on training for the respective radiation generating device to be used.

After receiving authorization from the ESH&A Health Physics Group and receiving your dosimetry you may begin using the RGD under the supervision of your Group Leader or designee.

1.3 Course Objective

This study guide illustrates and reinforces the skills and knowledge needed for RGD operators in the basics of safe operation of RGDs. Upon completion of this training course, the participant will have the knowledge to work safely in areas controlled for radiation generating device use by employing appropriate radiological safety practices.

1.4 Course Overview

Radiological Worker II (RW II) training for RGD usage is required for the worker whose job assignment involves entry into the Radiological Buffer Areas or Controlled Areas, which are the physical barriers surrounding the X-ray systems, and/or the areas designated as high or very high radiation areas near the X-ray tubes. This course is designed to prepare the worker to work safely around RGDs; and present methods to use to ensure individual radiation exposure is maintained ALARA.

Successful Completion (Evaluation Criteria) – At the completion of the course the participant must obtain a score of 80% or higher on a written exam. Section assessments are periodically placed throughout this guide to highlight topics of interest. Completing the questions in these parts will help prepare you for the final exam.

1.5 RWII Retraining

All individuals who use radiation generating devices at Ames Laboratory must possess a basic understanding of ionizing radiation and its potential hazards as well as knowledge of the particular rules and regulations governing radiation generating devices. Federal regulations, 10 CFR 835 requires that retraining be conducted every 24 months. At Ames Laboratory this requires the completion of a written exam and *Radiation Survey Instrument Refresher Training*.

1.6 Regulations and Guidance

The prime compliance document for occupational radiation protection at Department of Energy (DOE) sites is the Code of Federal Regulations, 10 CFR 835, "Occupational Radiation Protection". To implement this regulation, the Ames Laboratory Radiological Protection Program (RPP) has been written to state how each of the safety requirements will be accomplished at the Laboratory. The Radiation Safety Manual presents the information and procedures that must be understood and practiced in order to ensure all users of ionizing radiation at Ames Laboratory are in compliance with existing regulatory requirements. Any resultant radiation exposures must be maintained ALARA.

The American National Standards Institute (ANSI) details safety guidelines for x-ray devices in two standards: one on analytical (x-ray diffraction and fluorescence) x-ray equipment and another on industrial (nonmedical) x-ray installations;

- ANSI N43.2-2001, *Radiation Safety for X-Ray Diffraction and Fluorescence Analysis Equipment* and

- ANSI N43.3-2008, *American National Standard for General Radiation Safety for Installations Using Non-Medical X-ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV).*

Guidance for Radiological Worker training is also provided by the Nuclear Regulatory Commission in 10 CFR 19.12 and 10 CFR 34.31.

Section Assessment #1

1) *What is the primary Federal Regulation that requires Ames Laboratory to have an occupational radiation protection program?*
2) *What is the name of the process by which the Ames Laboratory Division/Institute/Program Directors give approval to research activities?*
3) *What is the frequency of refresher training for individuals who use radiation generating devices?*

2.0 RADIATION PROTECTION BASICS

Radiation as used in this study guide means alpha particles, beta particles, gamma rays, x-rays, neutrons, high-speed electrons, high speed protons, and other particles capable of producing ions. Radiation that has enough energy to cause ionization is called ionizing radiation. Radiation, as used in this guide, does not include non-ionizing radiation, such as radio waves or microwaves, or visible, infrared, or ultraviolet light.

An atom usually has a number of electrons equal to the number of protons in its nucleus so that the atom is electrically neutral. A charged atom, called an *ion,* can have a positive or negative charge. Free electrons also are called ions. An ion is formed when ionizing radiation interacts with an orbiting electron and causes it to be ejected from its orbit, a process called *ionization.* This leaves a positively charged atom (or molecule) and a free electron. Simply put ionizing radiation is radiation that can cause ionization of the material it passes through. That is, it removes electrons from atoms as it moves through matter.

2.1 Background Radiation

Background radiation, to which everyone is exposed, comes from both natural and manmade sources. Natural background radiation can be categorized as cosmic and terrestrial. Radon is the major contributor to terrestrial background. The most common sources of manmade background radiation are medical procedures and consumer products.

The average background dose to the general population from both natural and manmade sources is about 360 mrem per year to the whole body. Naturally occurring sources contribute an average of 200 mrem per year from radon daughters, about 40 mrem per year from internal emitters such as potassium-40, about 30 mrem per year from cosmic sources, and about 30 mrem per year from terrestrial sources such as naturally occurring uranium and thorium. Manmade sources contribute an average of about 60 mrem per year to the whole body from medical procedures such as chest X-rays.

2.2   ALARA

The effects of chronic exposure to low levels of radiation are not exactly known. It is assumed there is a small risk to any dose. With this in mind the principle of keeping doses to radiation **A**s **L**ow **A**s **R**easonably **A**chievable (ALARA) is a major part of radiation safety policy at Ames Laboratory.

2.3   Exposure Reduction Techniques

How can exposure to radiation be minimized? There are four physical factors that affect the exposure level in a radiation field: 1) distance, 2) time, 3) shielding, and 4) output factors (kV, mA).

- Exposure varies as the inverse square of the distance (assuming a point source, as from scattering). Maximize the distance by moving away from the source of the radiation. (Inverse square law, $I_2 = I_1 ((D_1)^2/(D_2)^2)$)
- Exposure increases linearly with time. Decrease the time spent in a radiation area by planning ahead.
- Exposure is inversely exponential with the thickness of shielding. Use shielding appropriate for the type of radiation. Lead, concrete, and steel are effective in shielding against x-rays and gamma ray sources.
- Exposure increases linearly with current (mA) and as the square of the potential (kV). Decrease the output factors to minimum levels while conducting alignments or sample area adjustments.

Section Assessment #2

1) *Name five types of ionizing radiation and give characteristics of each.*
2) *List the four methods for reducing radiation exposure.*
3) *What does ALARA mean relative to occupational radiation exposures?*

3.0   FUNDAMENTALS OF X-RAY PHYSICS

In 1895, the German professor, Wilhelm Roentgen was performing experiments with high speed electrons generated by an electron tube. During the course of his experiments, he discovered the interaction of these electrons with matter produced a form of highly penetrating radiation which he termed x-rays.

The ability of x-rays to penetrate matter differentially, as a function of density and elemental composition, was recognized almost immediately after their discovery and led to widespread applications for observing the internal structure of various objects, including the human body. Progressive improvements in x-ray technology throughout the 1900s have greatly expanded the uses of x-ray devices as research tools.

3.1   Nature of X-Rays

X-rays and gamma rays are a form of electromagnetic radiation. X-rays differ from gamma rays in their point of origin. Gamma rays originate from within the atomic nucleus, whereas x-rays originate from the electrons outside the nucleus and from free electrons decelerating in the vicinity of atoms (i.e., bremsstrahlung).

X-rays consist of photons of electromagnetic radiation and are distinguished from gamma rays only by their origin. Whereas gamma rays arise from transitions in the nuclei of radioactive atoms, x-rays are produced from electron shifts around the nucleus of the atom. Other types of electromagnetic radiation include radio waves, microwaves, infrared, visible light, and ultraviolet. The types of radiation are distinguished by the amount of energy carried by the individual photons.

All electromagnetic radiation consists of photons, which are individual packets of energy. For example, a household light bulb emits about 10^{21} photons of light (non-ionizing radiation) per second. The energy carried by individual photons, which is measured in electron volts (eV), is related to the frequency of the radiation. See the following table for different types of electromagnetic radiation and their typical photon energies.

Electromagnetic Radiation		
Type	**Typical Photon Energy**	**Typical Wavelengths**
radio wave	1 ueV	1 m
microwave	1 meV	1 mm (10^{-3}m)
infrared	1 eV	1 um (10^{-6}m)
red light	2 eV	6000 Angstrom (10^{-10}m)
violet light	3 eV	4000 Angstrom
ultraviolet	4 eV	3000 Angstrom
X-ray	100 keV	0.1 Angstrom
gamma ray	1 MeV	0.01 Angstrom

X-rays and gamma rays both ionize atoms. The energy required for ionization varies with material (e.g., 34 eV in air, 25 eV in tissue) but is generally in the range of several eV. A 100 keV x-ray can potentially create thousands of ions.

Gamma photons often have more energy than x-ray photons. For example, diagnostic x-rays are about 40 keV, whereas gammas from cobalt-60 are over 1 MeV. There are many exceptions. For example, gammas from technicium-99m are 140 keV, and the energy of x-rays from a high-energy radiographic machine may be as high as 10 MeV.

3.2 Production of X-Rays

There are two principal mechanisms by which x-rays are produced. The first mechanism involves the rapid acceleration of a high speed electron as it enters the electrical field of a nucleus. During this process the electron is deflected and emits a photon of x-radiation. This type of x-ray is often referred to as *bremsstrahlung* (meaning *braking radiation* in German). For a given source of electrons, a continuous spectrum of bremsstrahlung will be produced up to the maximum energy of the electrons (See Figure 1).

Figure 1: *Bremsstrahlung* (meaning *braking radiation* in German)

Generation of Bremsstrahlung
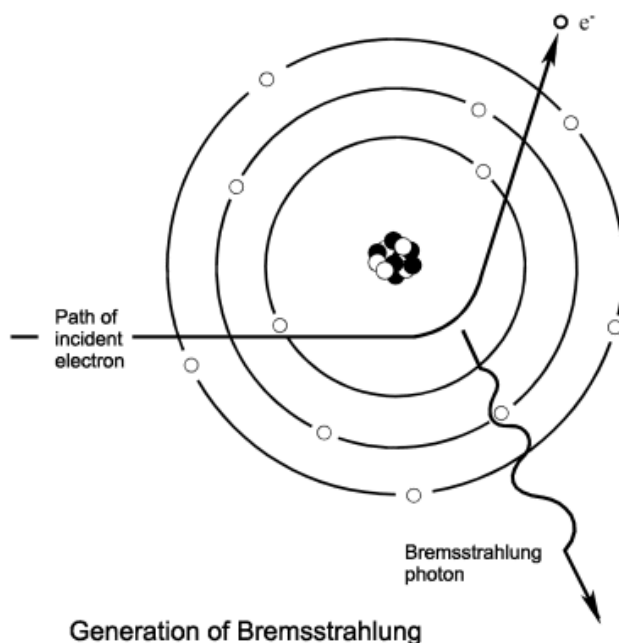
The second mechanism by which x-rays are produced is through transitions of electrons between atomic orbits. Such transitions involve the movement of electrons from outer orbits to vacancies within inner orbits. In making such transitions, electrons emit photons of x-radiation with discrete energies given by the differences in energy states at the beginning and end of the transition. Because such x-rays are distinctive for the particular element and transition, they are called characteristic x-rays (See Figure 2).

Figure 2: Characteristic X-rays

Generation of characteristic radiation
a) Ejection of orbital electrons
b) Emission of characteristic photons
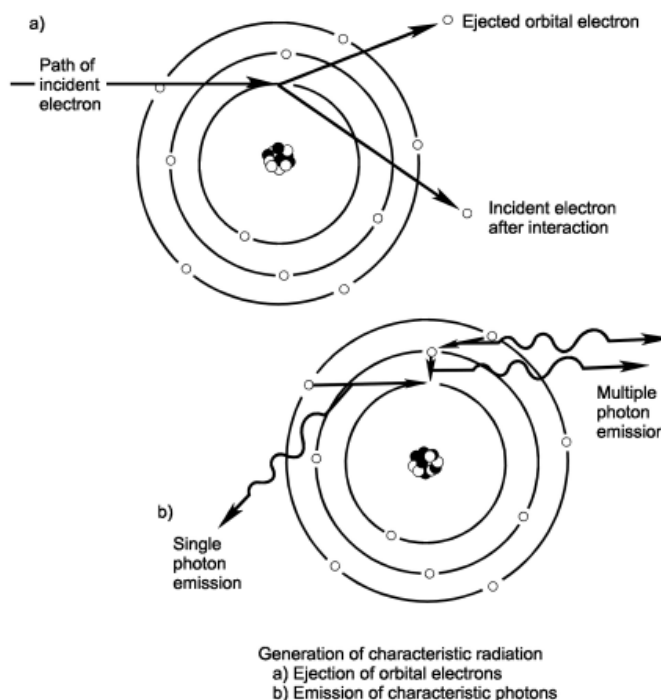
When electrons change from one atomic orbit to another, characteristic x-rays are produced. The individual photon energies are characteristic of the type of atom and can be used to identify very small quantities of a particular element. For this reason, they are important in analytical x-ray applications at research laboratories.

Both of these basic mechanisms are involved in the production of x-rays in an x-ray tube. Figure 3 is a schematic diagram of a standard x-ray tube. A tungsten filament is heated to 2000°C to emit electrons. These electrons are accelerated in an electric field toward a target (often tungsten sometimes molybdenum or copper). The interaction of electrons in the target results in the emission of a continuous bremsstrahlung spectrum along with characteristic x-rays from the particular target material.

Figure 3: Diagram of a standard X-ray Tube
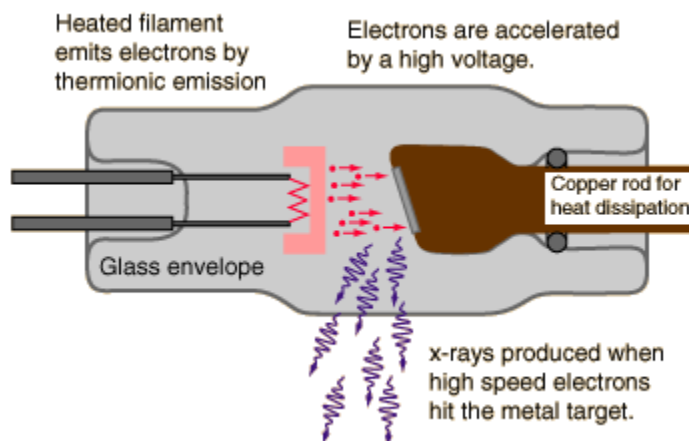
We have seen that x-rays are produced whenever high-speed electrons collide with a metal target. Any x-ray tube must contain (a) a source of electrons, (b) a high accelerating voltage, and (c) a metal target. Furthermore, since most of the kinetic energy of the electrons is converted into heat in the target, the latter is almost always water-cooled to prevent it from melting.

All x-ray tubes contain two electrodes, an anode (the metal target) maintained, with few exceptions, at ground potential, and a cathode, maintained at a high negative potential, normally of the order of 30,000 to 50,000 volts for diffraction work. X-ray tubes may be divided into two basic types, according to the way in which electrons are provided: gas tubes, in which electrons are produced by the ionization of a small quantity of gas (residual air in a partly evacuated tube), and filament tubes, in which the source of electrons is a hot filament.

All x-ray tubes have a maximum power rating which cannot be exceeded without injury to the tube. This limit is fixed by the amount of heat that can be dissipated by the target and is usually stated by the manufacturer in terms of the maximum allowable tube current (in mA) for a given tube voltage (in kV).

Since an x-ray tube is less than one percent efficient in producing x-rays and since the diffraction of x-rays by crystals is far less efficient than this, it follows that the intensities of diffracted x-ray beams are extremely low. In fact, it may require as much as several hours exposure to a photographic film in order to detect them at all. Constant efforts are therefore being made to increase the intensity of the x-ray source. One solution to this problem is the rotating-anode tube, in which rotation of the anode continuously brings fresh target metal into the focal-spot area and so allows a greater power input without excessive heating of the anode. The shafts rotate through vacuum-tight seals in the tube housing. Such tubes can operate at a power level 5 to 10 times higher than that of a fixed-focus tube, with corresponding reductions in exposure time. They are common in the area of radiography but not often used for diffraction.

Some diffraction methods require extremely fine x-ray beams. Such beams are most efficiently produced by special demountable x-ray tubes, called microfocus tubes, in which special attention is paid to achieving a very small focal spot. The design problem (fine focusing of the electron beam) is similar to that of the electron microscope or the x-ray microprobe. One focusing method is electrostatic and maintains the focusing cup around the filament at a potential of a few hundred volts more negative than the filament, thus concentrating the electrons into a narrower beam.

The focal spots of these tubes have areas of less than one percent of those of conventional tubes. Typical sizes are 0.1 X 1 mm for a line focus and 0.05 mm (= 50 mm) diameter for a circular focus.

The maximum power at which an x-ray tube can operate continuously is limited by the rate at which the target can be cooled. But if the tube is operated for only a small fraction of a second, a pulse of x-rays can be obtained at a very high power level without any cooling. This can be done by slowly charging a bank of capacitors and then abruptly discharging them across a special x-ray tube. In this way an x-ray pulse lasting about 30 nanoseconds at a peak voltage of 300 kV and a peak current of 5000 amperes has been produced. (Such a brief flash of x-rays is useful only if its results can be recorded.)

If increased attention is given, during the design of an x-ray tube, to focusing of the electron beam and to the shape and placement of the target, the intensity of the beam issued from the tube can be made about as large as that from a conventional tube, but with a power input of one-tenth or less. As a result, water cooling is not needed; air cooling is sufficient. This feature is important for portable apparatus. These tubes are small, only about 4 to 8 inches in length, and operate typically at a voltage of about 50 kV and a tube current of the order of 1 mA, as compared to 10 mA or more in conventional tubes.

3.3   Photon Energy and Power

It is important to distinguish between the energy of individual photons in an x-ray beam and the total energy of all the photons in the beam. It is also important to distinguish between average power and peak power in a pulsed X-ray device. Typically, the individual photon energy is given in electron volts (eV), whereas the power of a beam is given in watts (W). An individual 100 keV photon has more energy than an individual 10 keV photon. However, an x-ray beam consists of a spectrum (a distribution) of photon energies and the rate at which energy is delivered by a beam is determined by the number of photons of each energy. If there are many more low energy photons, it is possible for the low energy component to deliver more energy.

The photon energy distribution may be varied by changing the voltage. The number of photons emitted may be varied by changing the current.

The power supplies for many x-ray devices do not produce a constant potential (D.C.) high voltage but instead energize the x-ray tube with a time varying or pulsating high voltage. Since the bremsstrahlung x-rays produced are a spectrum of energies up to a maximum equal to the electron accelerating maximum voltage, the accelerating voltage

of the x-ray device is often described in terms of the peak kilovoltage or kVp.

A voltage of 50 kVp will produce a spectrum of x-ray energies with the theoretical maximum being 50 keV. The spectrum of energies is continuous from the maximum to zero. X-ray beams are typically filtered to minimize the low-energy component. Low-energy x-rays are not useful in radiography, but can deliver a significant dose.

The total number of photons produced by an x-ray device depends on the current, which is measured in amperes, or amps (A). The current is controlled by increasing or decreasing the number of electrons emitted from the cathode. The higher the electron current, the more x-ray photons are emitted from the anode. Many x-ray devices have meters to measure current. However, as mentioned above, x-rays can be produced by voltage even if the current is too low to read on the meter. This is sometimes called dark current. This situation can cause unnecessary exposure and should be addressed in SOPs or work documents.

3.4   Interaction of X-Rays with Matter
X-rays transfer their energy to matter through chance encounters with bound electrons or atomic nuclei. These chance encounters result in the ejection of energetic electrons from the atom. Each of the electrons liberated goes on to transfer its energy to matter through thousands of direct ionization events (i.e. events involving collisions between charged particles). Since x-rays and gamma rays transfer energy in this "indirect" manner, they are referred to as "indirectly ionizing radiations".

Because the encounters of photons with atoms are by chance, a given x-ray has a finite probability of passing completely through the medium it is traversing. The probability that an x-ray will pass completely through a medium depends upon numerous factors including the energy of the x-ray and the medium's composition and thickness.

Section Assessment #3
1) *Name the two basic types of electromagnetic radiation and give characteristics of each.*
2) *Define the term photon.*
3) *Briefly describe the mechanisms by which X-rays are produced.*

4.0   RADIATION QUANTITIES AND TERMS
The following quantities and terms are essential to the description and measurement of various forms of ionizing radiation.

4.1   Exposure
Exposure is a measure of the strength of a radiation field at some point. It is usually defined as the amount of charge (i.e., sum of all ions of one sign) produced in a unit mass of air when the interacting photons are completely absorbed in that mass. The most commonly used unit of exposure is the "roentgen" (R) which is defined as the amount of X or gamma radiation which produces 2.58×10^{-4} coulombs of charge per kilogram of dry air. In cases where exposure is to be expressed as a rate, the unit would be R/hr or, more commonly, milli-roentgen per hour (mR/hr).

4.2 Absorbed Dose

Whereas exposure is defined for air, the absorbed dose is the amount of energy imparted by radiation to a given mass of any material. The most common unit of absorbed dose is the "rad" which is defined as 100 ergs of energy per gram of the material in question. Absorbed dose may also be expressed as a rate with units of rad/hr or milli-rad/hr.

4.3 Dose Equivalent

Although the biological effects of radiation are dependent upon the absorbed dose, some types of particles produce greater effects than others for the same amount of energy imparted. In order to account for these variations when describing human health risk from radiation exposure, the quantity "dose equivalent" is used. This is the absorbed dose multiplied by certain "quality" and "modifying" factors indicative of the relative biological-damage potential of the particular type of radiation. The unit of dose equivalent is the "rem" or "milli-rem." Dose equivalent may likewise be expressed as a rate with units of rem/hr or milli-rem/hr. For gamma or x-ray exposures, the numerical value of the rem is essentially equal to that of the rad.

4.4 Shielding

Shielding is any material, which is placed around or adjacent to a source of penetrating radiation for the purpose of attenuating the exposure rate from the source. For shielding X-rays, materials composed of high atomic number elements such as lead are highly effective.

4.5 Half-Value Layer

The half-value layer is that thickness of a given material (i.e. shielding) required to reduce the exposure rate from a source of gamma or x-rays to one-half its unshielded value.

Section Assessment #4
Define the following terms:
Exposure, Absorbed Dose, Dose Equivalent, Shielding and Half-Value Layer

5.0 BIOLOGICAL EFFECTS OF IONIZING RADIATION

The energy deposited by ionizing radiation as it interacts with matter may result in the breaking of chemical bonds. It is called ionizing radiation because it contains enough energy to displace an electron from its orbit around a nucleus. If the irradiated matter is living tissue, such chemical changes may result in altered structure or function of constituent cells. These changes may, in turn, be manifested as one or more possible effects at the level of the organism.

5.1 Mechanisms of Radiation Damage

Because the cell is composed mostly of water, less than 20% of the energy deposited by ionizing radiation is absorbed directly by macromolecules. More than 80% of the energy deposited in the cell is absorbed by water molecules with the resultant formation of highly reactive free radicals: $H_2O \longrightarrow H^+ + OH^-$

These radicals and their products (e.g., hydrogen peroxide) may initiate numerous chemical reactions, which result in damage to macromolecules and a corresponding alteration of structure or function. Damage produced within a cell by the radiation-induced formation of free radicals is described as being an indirect action of radiation.

5.2 Radio-sensitivity

Radio-sensitivity is the relative susceptibility of cells, tissues, organs, organisms and other substances to the energetic actions of radiation. The cell nucleus is the major site of radiation damage leading to cell death. This is due to the importance of the DNA within the nucleus in controlling all cellular function. Damage to the DNA molecule may prevent it from providing the proper template for the production of additional DNA or RNA. This hypothesis is supported by research, which has shown that cells are most sensitive to radiation damage during reproductive phases (i.e., during DNA replication). In general, it has been found that cell radio-sensitivity is directly proportional to reproductive capacity and to the degree of cell differentiation. Table 1 presents a list of cells, which generally follow this principle.

TABLE 1

List of Cells in Order of Decreasing Radio-sensitivity		
Very Radio-sensitive	**Moderately Radio-Sensitive**	**Relatively Radio-Sensitive**
Mature lymphocytes Erythroblasts and Spermatagonia Basal cells Endothelial cells	Osteoblasts Granulocytes and Osteocytes Sperm Erythocytes	Fibrocytes Chondrocytes Muscle and Nerve Cells

The considerable variation in the radio-sensitivities of various tissues is due, in part, to the differences in the sensitivities of the cells that compose the tissues. Also important in determining tissue sensitivity are such factors as the state of nourishment of the cells, interactions between various cell types within the tissue, and the ability of the tissue to repair itself.

The relatively high radio-sensitivity of tissues consisting of undifferentiated, rapidly dividing cells suggest that, at the level of the human organism, a greater potential exists for damage to the fetus or young child than to an adult for a given dose. This has, in fact, been observed in the form of increased birth defects following irradiation of the fetus and an increased incidence of certain cancers in individuals who were irradiated as children.

5.3 Human Health Effects

The effects of ionizing radiation described at the level of the human organism can be divided broadly into two categories: stochastic or non-stochastic effects.

5.3.1 Stochastic Effects

As implied from the name "stochastic", these are effects that occur by chance. Stochastic effects caused by ionizing radiation consist primarily of genetic effects and cancer; as the dose to an individual increases, the probability that cancer or a genetic

effect will occur also increases. At no time, even for high doses, is it certain that cancer or genetic damage will result. Similarly, for stochastic effects, there is no threshold dose below which it is relatively certain that an adverse effect cannot occur. In addition, because stochastic effects can occur in unexposed individuals, one can never be certain that the occurrence of cancer or genetic damage in an exposed individual is due to radiation.

5.3.2 Non-stochastic Effects

Unlike stochastic effects, non-stochastic effects are characterized by a threshold dose below which they do not occur. In addition, the magnitude of the effect is directly proportional to the size of the dose. Furthermore, for non-stochastic effects, there is a clear causal relationship between radiation exposure and the effect. Examples of non-stochastic effects include sterility, erythema (skin reddening), ulceration, and cataract formation. Each of these effects differs from the other in both its threshold dose and in the time over which this dose must be received to cause the effect (i.e., acute vs. chronic exposure).

5.4 Factors Influencing the Occurrence of Health Effects

The type and probability of occurrence of health effects resulting from exposure to X-rays or other ionizing radiations is a function of several interrelated factors.

5.4.1 Dose and Dose Rate

The effect of ionizing radiation upon humans or other organisms is directly dependent upon the size of the dose received. The dose, in turn, is dependent upon a number of factors including the strength of the source, the distance from the source to the affected tissue, and the time over which the tissue is irradiated.

The ability of a given dose of ionizing radiation to cause health effects is influenced by the rate at which the dose is imparted. Because of various repair process which occur within the human body, a given dose of radiation in excess of that needed to produce a particular non-stochastic effect may, in fact, not produce such an effect if the dose is imparted over a relatively long period of time (i.e. chronic exposure). It is conservatively assumed that dose rate is not a critical factor in controlling the probable occurrence of stochastic effects such as cancer or genetic damage.

5.4.2 Chronic vs. Acute Exposures

Long-term exposures to relatively low levels of ionizing radiation are referred to as chronic exposures. As indicated by the previous section, such exposures have little potential for inducing non-stochastic health effects and are of concern because of their potential for initiating cancer or genetic damage. Short-term exposures to relatively high levels of ionizing radiation are referred to as acute exposures. Such exposures have the potential for producing both non-stochastic effects (e.g. erythema, epilation, and ulceration) as well stochastic effects (e.g. cancer) in the irradiated tissue.

5.4.3 Whole Body vs. Localized Exposure

The effectiveness of a given dose of external radiation in causing biological damage is dependent upon the portion of the body irradiated. For example, because of differences in the radio-sensitivity of constituent tissues, the hand is far less likely to suffer biological

damage from a given dose of radiation than are the gonads. Similarly, a given dose to the whole body has a greater potential for causing adverse health effects than does the same dose to only a portion of the body.

Section Assessment #5
1) Describe how free radicals are formed and how they damage the body.
2) Define the term radio-sensitivity and give two examples of highly radio-sensitive cells.
3) What is the difference between a stochastic effect and non-stochastic effect?
4) What are the three factors that influence the occurrence of health effects after an exposure to radiation?

6.0 EXPOSURE LIMITS

Concern over the biological effects of ionizing radiation began shortly after the discovery of x-rays in 1895. From that time to the present, numerous recommendations regarding occupational exposure limits have been proposed and modified by various radiation protection groups, the most important being the International Commission on Radiological Protection (ICRP). These guidelines have, in turn, been incorporated into regulatory requirements for controlling the use of materials and devices emitting ionizing radiation.

Table 2 Summary of Dose Limits [10 CFR 835.202, 1003(a)(1), (a)(2)]

Type Of Exposure	Limit
General Employee: Whole Body (internal + external) (TEDE)	5 rem/year
General Employee: Lens of Eye (external)	15 rem/year
General Employee: Extremity (hands and arms below the elbow;	50 rem/year
General Employee: Any organ or tissue (other than lens of eye)	50 rem/year
Declared Pregnant Worker: Embryo/Fetus (internal and external)	0.5 rem/gestation period
Minors: Whole body (internal + external)	0.1 rem/year
Minors: Lens of the eye, skin, and extremities	10% of General Employee

Notes:
1. The weighting factors in Appendix 2B, 10 CFR 835 shall be used in converting organ dose equivalent to effective dose equivalent for the whole body dose.
2. The annual limit of dose to "any organ or tissue" is based on the committed dose equivalent to that organ or tissue resulting from internally deposited radionuclides over a 50-year period after intake plus any deep dose equivalent to that organ from external exposures during the year.
3. Exposures due to background radiation, as a patient undergoing therapeutic and diagnostic medical procedures, and participation as a subject in medical research programs shall not be included in either personnel radiation dose records or assessment of dose against the limits in this Table.
4. See Appendix 2C for guidance on non-uniform exposure of the skin.
5. Whole body dose (TEDE) = effective dose equivalent from external exposures + committed effective dose equivalent from internal exposures.
6. Lens of the eye dose equivalent = dose equivalent from external exposure determined at a tissue depth of 0.3 cm.
7. Shallow dose equivalent = dose equivalent from external exposure determined at a tissue depth of 0.007 cm.

6.1 Basis of Recent Guidelines

In general, the guidelines established for radiation exposure have had as their principle objectives: (1) the prevention of acute radiation effects (e.g., erythema, sterility), and (2) the limiting of the risks of late, stochastic effects (e.g., cancer, genetic damage) to "acceptable" levels. Numerous revisions of standards and guidelines have been made over the years to reflect both changes in the understanding of the risk associated with various levels of exposure and changes in the perception of what constitutes an "acceptable" level of risk.

Current guidelines for radiation exposure are based upon the conservative assumption that there is no safe level of exposure. In other words, even the smallest exposure has some probability of causing a late effect such as cancer or genetic damage. This assumption has led to the general philosophy of not only keeping exposures below recommended levels or regulatory limits but of also maintaining all exposures ALARA. This is a fundamental tenet of current radiation safety practice.

6.2 Regulatory Limits for Occupational Exposure

Many of the recommendations of the ICRP and other radiation protection groups regarding radiation exposure have been incorporated into regulatory requirements by various countries. For Department of Energy facilities, radiation exposure limits are found in Title 10, Part 835 of the Code of Federal Regulations (l0 CFR 835). Table 2 provides a summary of the dose limits for occupational external exposures, for those designated at radiological workers.

6.3 Recommended Exposure Limits for Pregnant Workers

Because of the increased susceptibility of the human embryo and fetus to damage from ionizing radiation, established dose limits to the embryo/fetus are much lower than for adults. 10 CFR 835.206(a) requires the dose equivalent to the embryo/fetus from the period of conception to birth, as a result of occupational exposure of a declared pregnant worker be limited to 500 mrem. Pregnant workers are encouraged to declare their pregnancy in writing to their supervisors; the Laboratory will then take steps to keep exposures within the stated limit. Forms for declaring pregnancy are available from ESH&A (G40 TASF).

6.4 Regulatory Limits for Non-occupational Exposure

For whole body exposure, those not designated as radiological workers, the non-occupational exposure limit is 100 mrem/yr. This is the limit for persons not designated as radiological workers. This is in addition to the 360 mrem/yr received, on average, by individuals in the U.S. from natural background radiation and manmade radiation sources. The 100 mrem/yr limit also applies to individuals under age 18 who work in the vicinity of radiation sources.

Section Assessment #6

1) *What is the primary radiation protection organization that sets occupational exposure limits?*
2) *What is the amount of exposure received annually by naturally occurring background radiation?*
3) *Allowable exposure to a declared pregnant work is (greater, less) than the allowable whole body exposure to a general employee.*

7.0 TYPES AND CHARACTERISTICS OF ANALYTICAL X-RAY SYSTEMS

Analytical x-ray systems generally consist of three basic components: an x-ray source, a specimen support or holder, and a detector. In a given experimental setup, these three components may be enclosed in one integral, commercially available unit or they may be three distinct systems assembled by the user. The way in which the basic components of the x-ray system are assembled depends largely upon the mode of operation. Analytical x-ray systems have two principal modes of operation: diffraction and fluorescence.

7.1 X-ray Diffraction

X-ray diffraction is used extensively for analyzing the structure and properties of solid materials. Figure 4 illustrates the basic configuration of a diffraction system. In this mode of operation, the primary beam from the target of the x-ray tube emerges from the machine through a collimator and strikes the sample, which diffracts it in a characteristic manner. The diffraction pattern is measured with photographic film or a radiation counter.

Figure 4: Schematic diagram of X-ray diffraction system
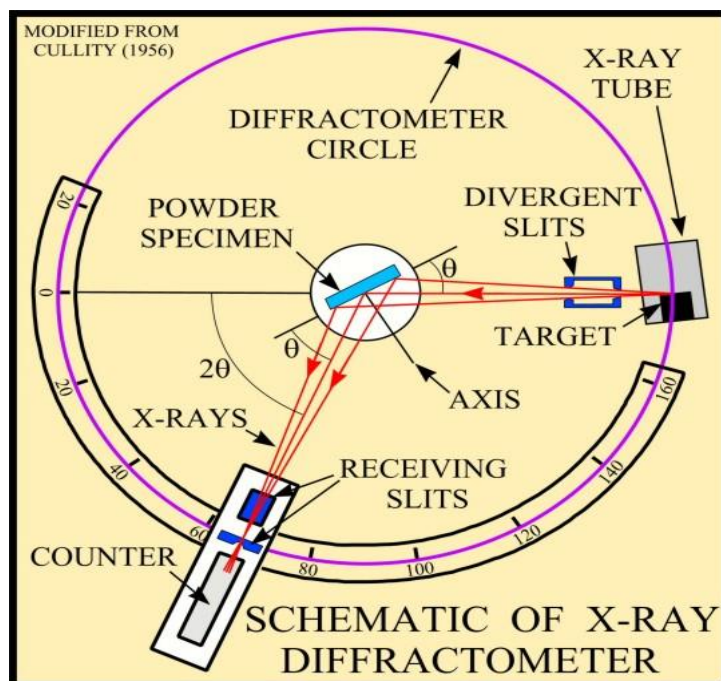
7.2 X-ray Fluorescence

X-ray fluorescence spectroscopy is an analytical method for determining the elemental composition of a sample. The configuration of a fluorescence system's components is illustrated by Figure 5. As shown, the primary radiation beam strikes the sample inside a shielded enclosure, and only scattered radiation and secondary radiation produced in the sample emerges from the machine for analysis.

Figure 5: Schematic diagram of X-ray fluorescence spectrometer
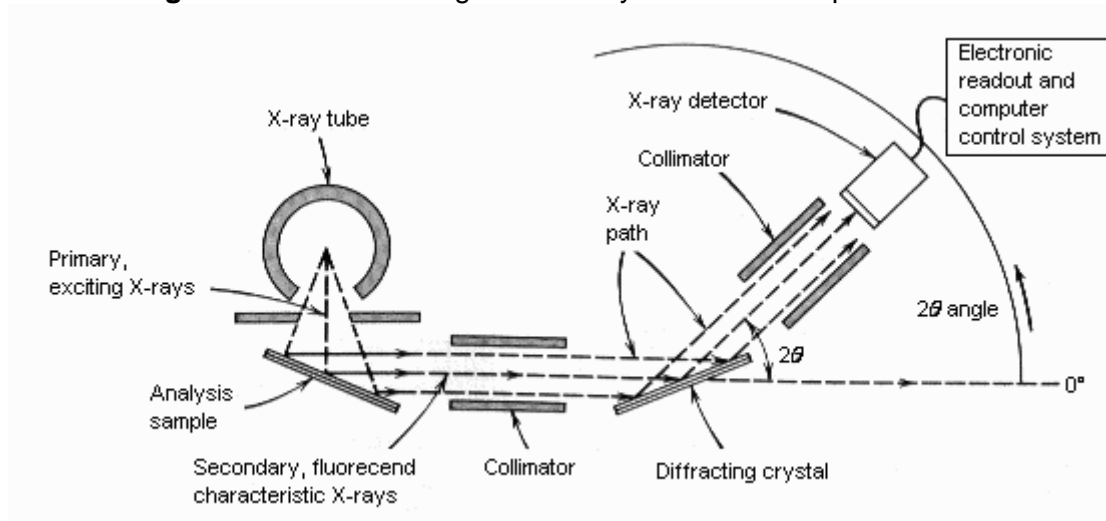
Section Assessment #7
1) *Name the three basic components of an analytical x-ray system.*
2) *Briefly describe the difference between x-ray diffraction and x-ray fluorescence.*

8.0 RADIATION HAZARDS OF ANALYTICAL X-RAY SYSTEMS

Because they utilize extremely high intensity x-ray beams, analytical x-ray systems have the potential for posing significant hazards if operated inappropriately. Radiation exposures can result not only from the primary beam but also from scattered (or diffracted) rays and secondary radiation from the sample or shielding material.

8.1 Primary X-ray Beam

The x-rays utilized most commonly in analytical systems have wavelengths in the range of 0.5 to 10 angstroms. These are often referred to as "soft" x-rays because of the ease by which they are absorbed in matter. While this characteristic enables soft x-rays to be readily shielded (generally requiring only a few millimeters of lead or iron), it also makes them particularly hazardous since they are highly absorbed even by soft tissue.

The primary beams from analytical x-ray systems are generally well collimated with beam diameters of less than one centimeter. Because of their intensity and their high degree of absorption in tissue, they can produce severe and permanent local injury from exposures of only a fraction of a second.

Potential exposure to the primary X-ray beam is generally not a major concern for analytical systems operating in the fluorescence mode since the beam in these systems are contained within a shielded enclosure. The possibility of leakage of the primary beam through the shield, however, cannot be discounted.

Exposure to the primary beam of diffraction units is a major concern. In fact, the greatest risk of acute accidental exposures from analytical systems occurs in manipulations of the sample to be irradiated by the direct beam in diffraction studies. Exposure rates on the order of 10,000 R/sec can exist at the tube housing port. At these levels, erythema would be produced from exposures of only 0.03 second and permanent injury could be inflicted in only 0.1 second. The fingers, of course, are the part of the body most at risk from such high exposures.

8.2 Diffracted X-ray Beam
For x-ray diffraction systems, the diffracted beam is also small and well collimated with an intensity of up to 80 R/hr. Prolonged or repeated exposures to a beam of this intensity could result in an individual exceeding the annual dose limit for the particular tissue irradiated.

8.3 Scattered and Secondary X-rays
Through interactions with the sample and shielding material, the primary beam in diffraction systems often produces diffuse patterns of scattered and secondary x-rays in the environment around the equipment. Exposure rates of 150 mR/hr near the shielded sample are not uncommon. In contrast, scattered and secondary radiation levels in the vicinity of a fluorescence system (where only secondary radiation emerges from the shielded target-sample assembly) is generally an order of magnitude less.

Section Assessment #8
1) *Define the term "soft X-rays."*
2) *The greatest risk of exposures from analytical systems occurs during what activity?*

9.0 HAZARD CONTROL MEASURES FOR X-RAY SYSTEMS
Requirements for controlling potential hazards associated with analytical x-ray systems are specified in most states by law. At Ames Lab these requirements are detailed in the Radiation Safety Manual. Portions of these hazard control and safety measures are summarized here.

9.1 Equipment Requirements

9.1.1 *Beam Entry Shut-off Device*
A device which prevents the entry of any portion of an individual's body into the primary beam path or which causes the beam to be shut off upon entry into its path shall be provided on all open-beam configurations.

9.1.2 *Shutters*
Shutters open and close a path for the X-ray beam. When a shutter is properly functioning and closed, no X-rays can pass beyond the shutter. On open-beam configurations, each port on the source housing shall be equipped with a shutter that cannot be opened unless a collimator or coupling has been connected to the port.

Figure 6:
Interlocked enclosure with shutter and enclosure status lights

Figure 7:
Interlocked enclosure with x-ray status light on the top of the unit

9.1.3   *Housing Interlock*
Each x-ray tube housing shall be equipped with an interlock that shuts off the tube if the tube is removed from the housing or if the housing is disassembled.

9.1.4   *Shielding Provided by Housing*
Each x-ray tube housing shall be constructed so that, with all shutters closed, the radiation, measured at a distance of five centimeters from its surface, is not capable of producing a dose in excess of 2.5 millirem in one hour.

9.1.5   *Warning Lights*
An easily visible warning light with the words "X-RAY ON" shall be located near any switch that energizes an x-ray tube and shall be illuminated only when the tube is energized (see Figures 4 & 5).

9.1.6   *Labeling*
All X-ray equipment shall be labeled with a readily discernible sign bearing the radiation symbol and the words (see Figures 4 & 5):
(1)"CAUTION - HIGH INTENSITY X-RAY BEAM" on the X-ray source housing; and
(2)"CAUTION RADIATION - THIS EQUIPMENT PRODUCES RADIATION WHEN ENERGIZED" near any switch that energizes the X-ray tube.

9.2 Area Requirements

9.2.1 Radiation Levels
The components of an analytical x-ray system shall be arranged and shall be sufficiently shielded to ensure that radiation levels near the controls cannot result in an individual receiving a dose in excess of 2.5 millirem whole body exposure in any one hour.

9.2.2 Surveys
Radiation surveys of all x-ray systems sufficient to show compliance with the radiation levels established in 9.2.1 must be performed:
1. Upon installation of the equipment and at least every twelve months thereafter.
2. Following any change in the number, type, or arrangement of components in the system.
3. Following any maintenance requiring the disassembly or removal of a system component.

These surveys shall be conducted by ESH&A and it is the responsibility of the x-ray system users to notify ESH&A if situation 2 or 3 should arise.

9.2.2.1 Survey requirement for X-ray User
The x-ray user shall conduct an x-ray survey when the system interlock has been placed into an off normal state or bypassed. X-ray systems with the capability of bypassing the interlock are required to have a Radiological Work Permit (RWP). Only persons on the system's RWP are authorized to bypass the system interlock.

9.2.3 Posting
Laboratory space containing x-ray equipment is labeled at the entry way(s) as an x-ray equipment laboratory. The interlocked Plexiglas barriers surrounding the x-ray systems shall be posted as a "CONTROLLED AREA" or "BUFFER AREA" as necessary, and the area immediately adjacent to all x-ray beam ports, whether open beam or closed beam, shall be posted with a sign which reads "CAUTION [OR DANGER] - HIGH RADIATION AREA" as appropriate.

9.3 Operating Requirements

9.3.1 Procedures
Standard operating procedures shall be written and available to all x-ray equipment workers.

9.3.2 Bypassing Safety Devices
No individual shall bypass a safety device or interlock unless the individual has obtained written approval from the Radiation Safety Officer. X-ray systems with the capability of bypassing the interlock are required to have a Radiological Work Permit (RWP). Only persons on the system's RWP are authorized to bypass the system interlock.

9.3.3 Altering System Components

No operation involving the removal or alteration of shielding materials, tube housing, shutter, collimators, or beam stops shall be performed until it has been determined that the beam is off and will remain off until safe conditions have been restored.

9.4 Personnel Monitoring Requirements

As a minimum, finger or wrist dosimeters shall be provided to and shall be used by all radiation generating device users. At Ames Laboratory, the Health Physics Group issues ring dosimeters (see Figure 8) to all users of x-ray devices and, if requested by the user, whole body badges in addition to the extremity dosimeters. Whole body monitors, on occasion, are provided to RGD workers coming in contact with equipment capable of exposing a major portion of the body. Annual exposure reports are distributed to dosimetry participants during the end of the first quarter of each year. This is a 10 CFR 835 requirement.

Dosimetry is used to provide an indication of the amount of external radiation exposure the wearer has received, and must be worn at all times when using the equipment. They should be stored in a central location away from the equipment and any heat sources to avoid exposure to the badges when they are not being worn. Badges are on a quarterly cycle. They are issued and old badges are collected by your Group Leader (or designee), returned to ESH&A and shipped to the dosimetry vendor for analysis. The dosimetry will not be issued to any individual until the required training has been completed.

At Ames Laboratory, thermoluminescent dosimeters (TLDs) in the form of ring badges are issued to all who operate X-ray equipment. Thermoluminescent dosimeters contain crystalline materials (lithium fluoride) that emit light if they are heated after having been exposed to radiation. The whole body badges typically contain several compartments of crystals with various shields to differentiate the types of radiation to which the badge and wearer are exposed.

Remember that dosimetry badges are to be worn only by the person to whom they are assigned and are not to be shared. They are to be worn only for work related to X-ray use research at the Laboratory.

Figure 8: Dosimetry ring badge

Figure 9: Geiger-Muller survey instrument
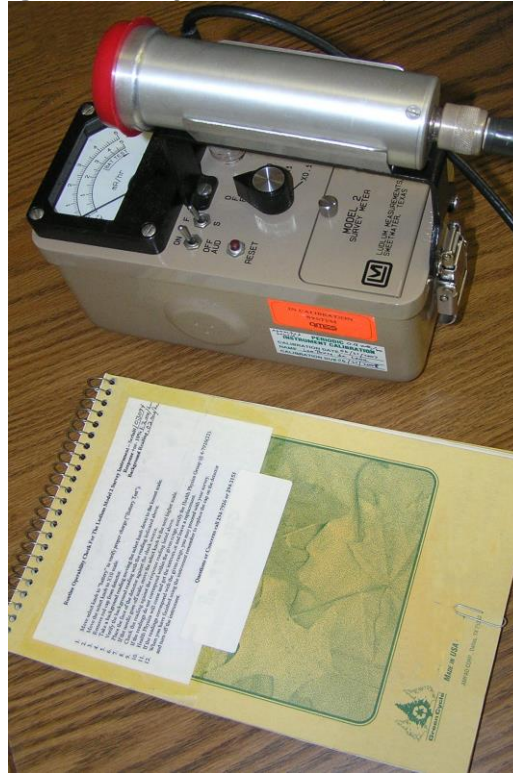
9.4.1 X-ray Detection Instrument

Each RGD system laboratory at Ames Laboratory is assigned a Geiger-Muller (GM) survey instrument with an end window detector, as shown in Figure 9 or a GM with a pancake probe. This type of instrument is effective for detecting scatter radiation. This instrument has been placed in your laboratory to be used to survey your respective x-ray unit before resuming routine operations any time that the unit or procedure for use of the unit are changed such that radiation output may be increased in intensity, penetration or distribution. Radiation surveys are also required during off normal x-ray system states such as bypassed interlocks. Surveys should be document in the survey meter logbook. It is advised to use the meter to check that radiation levels are not elevated prior to accessing the sample area.

Prior to using the GM instrument you must perform an operation check. Pre-operational Checks involve the following;
- Calibration sticker (instrument is calibrated annually, instruments past their calibration date should not be used and should be reported to the HPG),
- Battery check,
- Physical damage inspection,
- Background check reading (document your reading in the instrument logbook),
- Source check reading (document your reading in the instrument logbook), and
- Document operational checks in the instrument logbook prior to using the instrument.

Note that readings taken during the pre-operational check should be within +/-10 % of previous readings already recorded in the instrument logbook. If a GM is outside +/-10% of previous readings report this to the HPG. If the GM fails any of the pre-operational checks it should not be used and your results should be reported to the HPG so a properly operating meter can be supplied to you.

Section Assessment #9
1) *Define the following control devices and how they work: 1) Beam entry shut-off device, 2) Shutters, and 3) Housing interlock*
2) *When are radiation surveys of X-ray systems required?*
3) *Define the term dosimetry.*
4) *Describe the primary type of dosimeter used at Ames Laboratory and how it works.*
5) *Name three things done during a pre-operational check of a Geiger-Muller survey instrument.*

10.0 RESPONSIBIITY FOR X-RAY SAFETY
The responsibility for maintaining radiation exposures from radiation generating devices ALARA is shared among the Ames Laboratory Line Management, the ESH&A office, the x-ray device Group Leader (activity supervisor), and x-ray device operators.

10.1 Ames Laboratory Leadership
In accordance with the specific requirements of Ames Laboratory's RPP, an ALARA Committee has been established that oversees the implementation of Laboratory policies and procedures for the safe use of radioactive materials and radiation generating devices. The Committee consists of members of Ames Laboratory's staff and faculty appointed by the Director for terms of three years. In addition, the ALARA Committee reviews all requests for use of radioactive materials and radiation generating devices, reviews records of personnel dosimetry, and decides whether or not authorization for use is to be granted.

10.2 ESH&A, Health Physics Group
ESH&A Health Physics Group is responsible for:
- Establishing requirements and standards,
- Offering consulting services and institutional training,
- Approving all purchases, moves, transfers, and alterations of x-ray equipment,
- Conducting laboratory inspections, surveying x-ray equipment, verifying the appropriate safety program requirements have been met, and affixing compliance labels to devices,
- Administering the personnel dosimetry program, and
- Coordinating with the Engineering Services Group for preventive maintenance and repair of the engineered x-ray barrier safety systems in Ames Laboratory spaces or owned by Ames Laboratory programs in ISU spaces. (Safety interlocks are checked every six months to ensure proper functionality.)

10.3 Group Leader/Activity Supervisor

The individual authorized by the ALARA Committee as the activity supervisor on an activity involving the use of radioactive material or a radiation generating device is responsible for all activities conducted under the scope of that authorization. This includes responsibility for ensuring that:

- All individuals working on the activity are appropriately trained and supervised.
- The ALARA Committee has formally authorized all individuals working on the activity.
- All rules, regulations, and procedures for the safe use of radiation generating devices are observed during the activity.
- An accurate record of radiation generating devices in his or her possession is maintained.
- The ESH&A Office is notified of any proposed changes in the storage or use of the radioactive material or a radiation generating device prior to the implementation of such changes.
- All uses of radiation are evaluated to further reduce exposures to individuals (ALARA).
- All radioactive sources or source material are protected from unauthorized access or removal.
- All SOPs are current and distributed appropriately.
- Maintain a list of qualified operators authorized for particular machines in each respective RGD laboratory as well as a system user logbook and maintenance logbook.

It is recommended that the system logbook contain the following information:

- Name of person performing maintenance on system and employer if outside contractor;
- The reason the maintenance was performed;
- Specific problems noted during maintenance;
- Repairs performed (if a modification to the system is performed, reference the date of approval from Group Leader and the ESH&A Office);
- Time and date the maintenance was performed; and
- Signature of the person who did the maintenance on the system

10.4 X-ray device Operators

Authorized X-ray-device operators are responsible for:

- Keeping his or her personal exposure as low as reasonably achievable,
- Wearing your ring dosimeters appropriately,
- Knowing and following the standard operating procedure for each machine operated,
- Knowing and following the operator safety protocols,
- Notifying their supervisors of any unsafe or hazardous work situations,
- Before reaching into the primary beam location, verifying that the beam shutter is closed or that machine power is off, and
- Completing all required training, and assist the laboratory supervisor in maintaining the required records (x-ray system logbooks).

Section Assessment #10
1) *Who oversees implementation of the Laboratory's RPP?*
2) *Name three things a Group Leader is responsible for relative to use of analytical x-ray systems at Ames Laboratory.*
3) *Name three things an x-ray device operator is responsible for relative to use of analytical x-ray systems at Ames Laboratory.*

11.0   RADIATION SAFETY REFERENCES

Radiation Protection, 3rd edition, Jacob Shapiro, Harvard University Press, Cambridge, Massachusetts, 1990.

Introduction to Health Physics, 3rd edition, Herman Cember, Pergamon Press, New York, NY 1996.

Radiologic Science for Technologists, 2nd edition, Stewart Bushong, The C.V. Mosby Company, St. Louis, Missouri, 1980.

The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980, National Academy Press, Washington, D.C., 1980.

Atoms, Radiation, and Radiation Protection, J.E. Turner, Pergamon Press, Oxford, England, 1995.